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Galactic Center Youth: Orbits and Origins of the Young Stars in the Central Parsec

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Abstract. We present new proper motions for the massive, young stars at the Galactic Center, based on 10 years of diffraction limited data from the Keck telescopes. Our proper motion measurements now have uncertainties of only 1-2 km/s and allow us to explore the origin of the young stars that reside within the sphere of influence of the supermassive black hole whose strong tidal forces make this region inhospitable for star formation. Their presence, however, may be explained either by *in situ* star formation in an accretion disk or as the remnants of a massive stellar cluster which spiraled in via dynamical friction. Earlier stellar velocity vectors were used to postulate that all the young stars resided in two counter-rotating stellar disks, which is consistent with both of the above formation scenarios. Our precise proper motions allow us, for the first time, to determine the orbital parameters of each individual star and thereby to test the hypothesis that the massive stars reside in two stellar disks. Of the 26 young stars in this study that were previously proposed to lie on the inner, clockwise disk, we find that nearly all exhibit orbital constraints consistent with such a disk. On the other hand, of the 7 stars in this study previously proposed to lie in the outer, less well-defined counter-clockwise disk, 6 exhibit inclinations that are inconsistent with such a disk, bringing into question the existence of the outer disk. Furthermore, for stars in the inner disk that have eccentricity constraints, we find several that have lower limits to the eccentricity of more than 0.4, implying highly eccentric orbits. This stands in contrast to simple accretion disk formation scenarios which typically predict predominantly circular orbits.

1. Introduction

The center of our Galaxy has been shown to harbor a supermassive black hole ($M_{SBH} \sim 3-4\times10^6$ M$_\odot$, e.g. [1, 2]) whose close proximity ($R_o \sim 7-8$ kpc, [1, 2, 3]) provides a unique laboratory for studying phenomena in normal galactic nuclei. One peculiar attribute of our Galactic center is the presence of a population of massive ($30-120$ M$_\odot$), young ($\lesssim 10$ Myr) stars within the sphere of influence of the black hole (see e.g. [4, 5]). The origin of such young stars is puzzling given that the present-day gas density is orders of magnitude too low to overcome the extreme tidal forces and collapse to form stars [6, 7]. Proposed resolutions to this "paradox of youth" include scenarios in which these young stars formed in a massive, self-gravitating accretion disk that was once present around the black hole [8] or alternatively,

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formed far from their current positions, outside the black hole's sphere of influence, as part of a massive star cluster which spiraled in via dynamical friction and deposited the most massive stars where we see them today [9].

Insight into the origins of the massive, young stars may be obtained through understanding the spatial distribution and stellar dynamics of this population. Already, high-resolution infrared imaging of young OB stars located less than $0''.5$ (3680 AU) from the black hole have yielded precise measurements of the stellar orbits which indicate that their orbital planes are randomly oriented [1, 10]. However, the central-arcsecond stars with measured orbits reside close enough to the black hole that their dynamics are likely to have been modified due to various precession mechanisms, which weakens any signature of their origin from their orbits. Orbital analysis of the young stars at larger radii has been limited due to the stars' smaller accelerations and the dominance of optical distortions beyond $0''.5$ [10]. Nonetheless, analyses using the stars' observed three-dimensional velocities have suggested that the stars at larger radii may lie in two perpendicular, counter-rotating disks with inner disk radii of around 1 arcsec [8, 11] and that there may be several co-moving groups or clusters of stars within the area [12, 13]. Both of the above possible formation scenarios predict that the stars should lie in a common orbital plane; however, formation in a self-gravitating accretion disk tends to suggest circular orbits while infalling cluster scenarios could give rise either to circular or eccentric orbits.

In this paper, we present an improved proper motion analysis in which new adaptive optics data allow us to correct for optical distortions and achieve stellar velocities with uncertainties reduced by as much as a factor of 10 (down to $\sim$1 km/s). We also attempt, for the first time, to extend stellar orbit techniques beyond the central arcsecond out to where the young stars within the central parsec may still hold a dynamical signature of their origins.

2. Observations and Analysis

This study uses high-resolution, 2 μm images of the Galaxy's central stellar cluster taken using both speckle and laser guide star adaptive optics (LGSAO) observing techniques at the 10 m Keck telescopes. Two new speckle data sets, taken in 2005, were combined with 25 existing speckle data sets from 1995-2004 [10, 13, 14, 15] and 4 LGSAO data sets from 2004 - 2005 [16]. Prior to LGSAO observations, the NIRC speckle data sets contained a small amount of residual geometric distortion. Although this distortion is negligible near the center of the images, where Sgr A* and the central arcsecond sources are located; the astrometric accuracy of stars at larger radii is dominated by this residual distortion term. Our LGSAO observations offer a substantial improvement in data quality over speckle imaging and, of particular interest to this study, have well characterized distortion. Simultaneous speckle and LGSAO observations have enabled us, for the first time, to fully characterize and correct optical distortion in the speckle data (Figure 1).

While many sources are detected in this rich data set, we focus our attention on a sample of 33 young stars for this study. The sample is selected to be all young stars spectroscopically identified with high confidence ("quality 2") in Paumard et al. [5] that are between $0''.8$ and $3''.2$ from Sgr A*. The inner radius is set by the approximate inner edge of the proposed disks and the outer radius is set by the speckle field of view (6" $\times$ 5"). For each star in this sample, the Keck imaging data set provides 15 - 31 astrometric measurements and, additionally, one or more radial velocity measurements are taken from the literature [5, 17, 18, 19, 20]. Velocities in the plane of the sky are derived from the astrometric measurements by fitting first order polynomials ($x = x_o + v_x * \Delta t$) to positions as a function of time, weighted by the positional uncertainties.

For the resulting sample of 33 young stars, we carried out orbit fitting for each star, assuming a Keplerian orbit model in which the gravitational potential arises from a single dominant point mass situated at the photometric centroid of Sgr A*. The mass and the distance to Sgr A* are

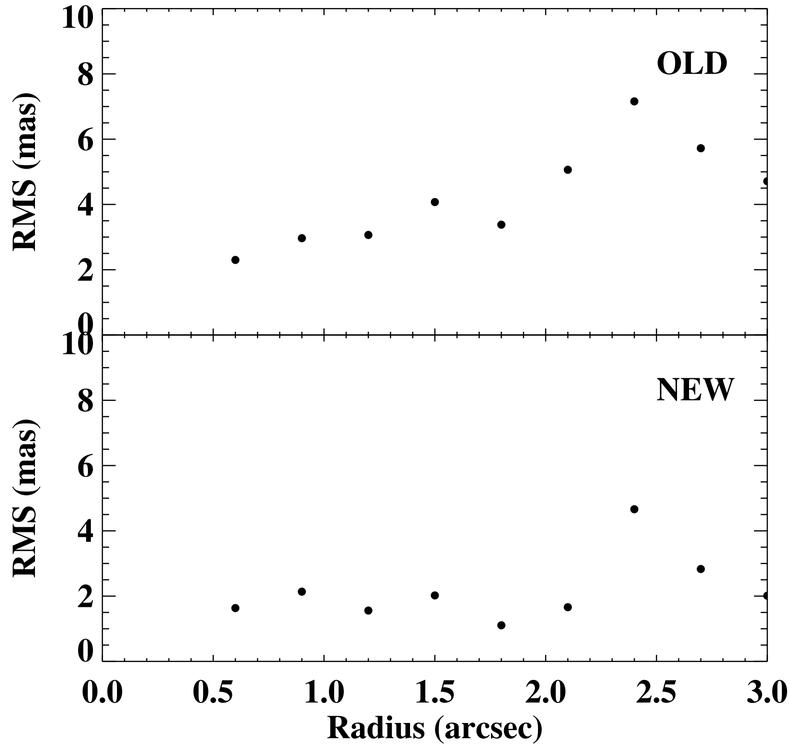

Figure 1. The improvement in positional accuracy at large radii as a result of correcting geometric distortion in speckle data sets. To characterize the systematic positional uncertainty, we take each star at each epoch and calculate the residual positional offset, which is defined as the difference between the measured position and the position as determined by the best fit velocity ($x = x_o + v * \Delta t$). Then the RMS of the residuals is calculated across all epochs for each star. All stars' resulting RMS values are sorted by the distance between the star and Sgr A* (which was at the center of the images) and then averaged over radius bins of $0''.3$. The radial trend is shown for data prior to the new distortion correction (top) and after the new distortion correction (bottom).

fixed at values set by S0-2's orbit with $M_\bullet$=3.69×10^6 $M_\odot$ and $R_\circ$=7.36 kpc ([2]). For each star, there are then six free parameters: period (P), eccentricity (e), time of periapse passage ($T_\circ$), inclination (i), position angle of the ascending node (Ω), and the longitude of periapse (ω), not all of which can be well constrained given that the stars only have significant measurements of the 2D positions, 3D velocities, and upper limits to accelerations (see [10] for detailed description of the orbital parameters). Orbit fitting is carried out by minimizing the χ^2 value between the data and the model using the Thiele-Innes method [21]. Uncertainties in the fits are characterized by fully exploring orbital parameter space and empirically determining those orbital solutions with $\chi^2 < \chi^2_{min} + 1$ for 1σ errors.

3. Results

The proper motion measurements, as shown in Figure 2, are as much as ten times better than our most recent work in [13] with typical absolute uncertainties of 1-2 km/s. This substantial improvement is primarily a result of a revised distortion solution for the NIRC-speckle data

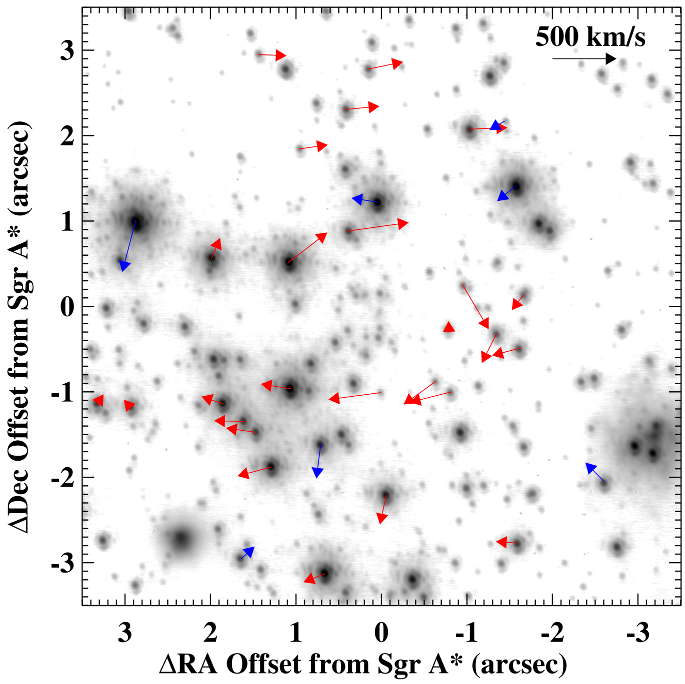

Figure 2. Proper motion vectors of spectroscopically confirmed young stars. Clockwise orbiting stars are drawn in red while counter-clockwise stars are shown in blue. These are overlayed on a K-band LGSAO image shown in grey scale.

sets. Given the high-precision positions and velocities, we attempt, for the first time, to fit orbits to these stars in order to constrain their accelerations and orbital parameters. Figure 3 shows the acceleration limits achieved for all the young stars in the sample as compared to the theoretical curve of acceleration as a function of radius. Assuming that each star is on a bound Keplerian orbit, the measured three-dimensional velocity sets an upper limit to the 3D distance between the star and Sgr A*. The observed 2-dimensional projected distance also sets a lower limit to the total 3D distance (Figure 3, *horizontal arrows*). Additionally, many of the stars show a significant lack of acceleration in the plane of the sky that, when combined with the distance constraints and the 3D velocity information, defines acceptable ranges of orbital parameters for each star. Figure 4 shows some resulting constraints for a sample star, IRS 16CC. These constraints on the orbital parameters can also be expressed as a constraint on the total 3D acceleration for each star (Figure 3, *vertical arrows*). The resulting orbits for the sample of young stars typically have two possible orbital solutions as a result of a degeneracy in the orbital parameter Ω (angle to the ascending node, see Figure 4, *middle*).

Constrained orbital parameters include the angle to the ascending node (Ω) and the inclination (i), which can be combined to determine the orientation of the orbital plane. Figure 5 shows the orientation for all the stars' orbital planes. For each star, the 3σ constraints on Ω and i translate into a cone into which the normal vector to the orbital plane points, and this cone is then projected onto a celestial sphere centered on Sgr A* as an elliptical region. All stars orbiting in a clockwise rotation in the plane of the sky are plotted in red and both of the degenerate solutions are plotted, one as a solid line and one as a dashed line. One of

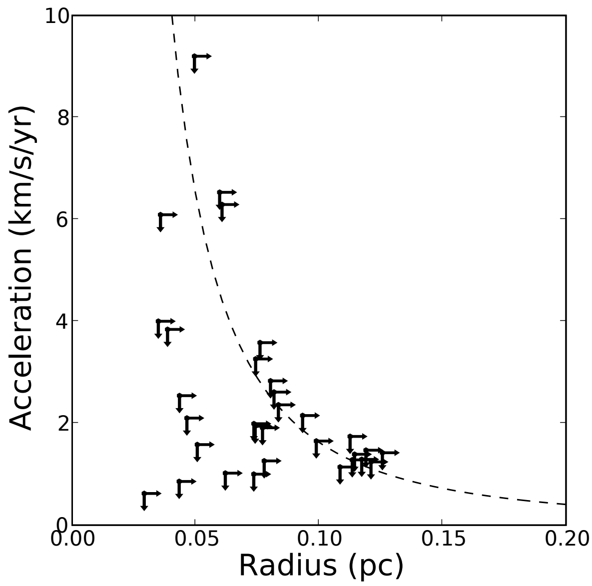

Figure 3. Acceleration limits for the sample of 33 young stars. The theoretical curve for acceleration as a function of total distance is plotted (dashed), as is each star's 3σ acceleration upper limit from orbit fitting (vertical arrow) and radius lower limit from the observed projected distance from the black hole (horizontal arrow).

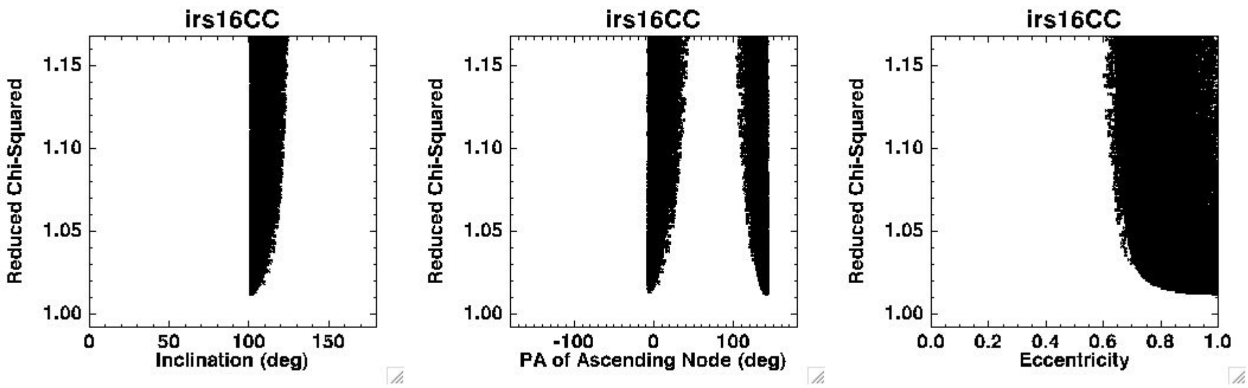

Figure 4. Projected χ^2 parameter space for several orbital elements from a sample star, IRS 16CC. The χ^2 space is mapped by running many trial orbits and those orbits that fall within a 3σ range of χ^2 values are plotted. The inclination (panel 1) and PA to the ascending node, Ω (panel 2), are used to determine the orientation of the orbital plane. This star has an additional constraint on the eccentricity (panel 3).

the solutions for the clockwise stars' normal vectors cluster around a common point indicating that these stars may lie on a common orbital plane. The counter-clockwise stars, plotted in blue, do not appear to cluster around any single point, suggesting that they do not lie on a common orbital plane. Over plotted in black are the candidate orbital planes proposed by [8] and [11] with updated values from [5] for the candidate plane normal vectors (solid black) and disk thickness (dashed black).

Stars in the inner disk also show evidence for eccentric orbits. For more edge-on orbits, a lower limit to the distance from Sgr A* coupled with particular directions of the 3D velocity vector will result in a lower limit to the eccentricity. Of the 26 stars in the clockwise disk, 10 of the stars have 3σ lower limits to their eccentricities of >0.2. Figure 6 shows the 3σ limit on eccentricities for all the stars in the sample. These eccentricity limits are robust as there is a sharp lower limit in chi-squared vs. eccentricity space (see Figure 4, *right* for an example).

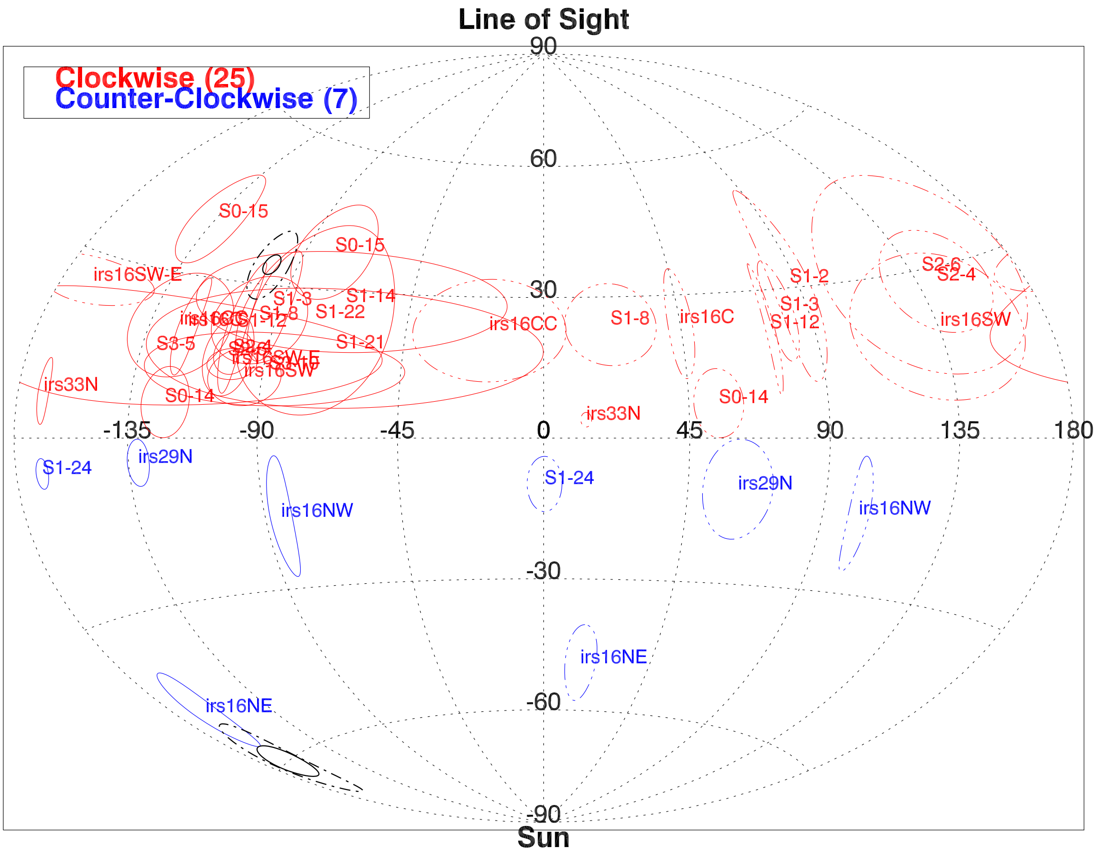

Figure 5. The distribution of orbital planes as determined from individual stellar orbits. The normal vector for each star's orbital plane, plus the associated uncertainty in that vector, describes a cone in 3D space. This cone can be projected as an elliptical region onto a celestial sphere centered on the black hole. The projected 3 sigma region of the normal vectors are plotted on an Aitoff projection of this celestial sphere with clockwise rotators in red and counter-clockwise in blue. For reference, those stellar orbits with normal vectors pointing toward or away from the Sun have face-on orbits as seen from Earth.

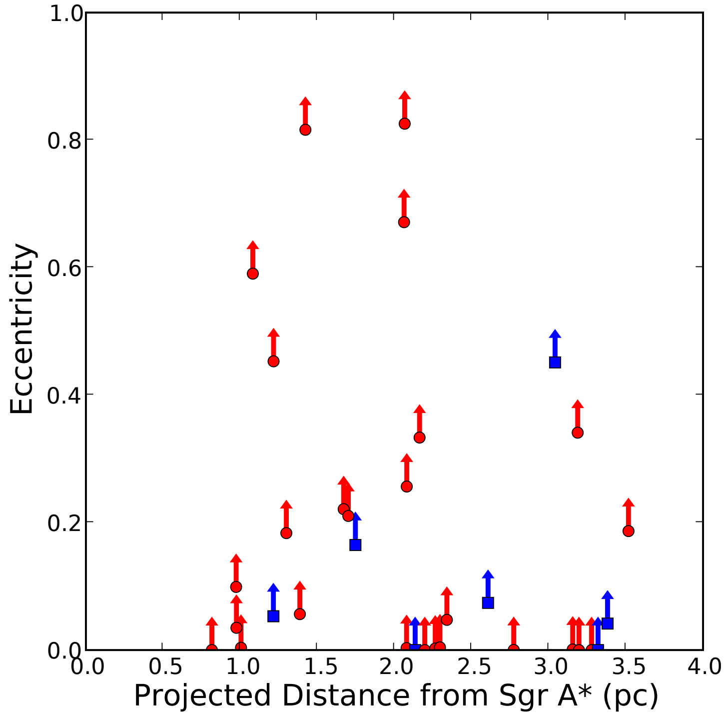

Figure 6. The distribution of eccentricities lower limits as determined from individual stellar orbits. Stars rotating with a clockwise orientation are plotted as red circles and counter-clockwise stars are plotted as blue squares.

4. Discussion

This first attempt at orbital fitting for young stars that reside outside the central arcsecond shows definitive evidence for one disk of clockwise rotating stars. The proposed second disk is not supported by observations of counter-clockwise stars within $\sim 3''$ of Sgr A*; however, our current observations cannot definitively rule out the existence of a 2nd disk until we expand our study to include more counter-clockwise rotating young stars at larger radii from Sgr A*.

Determining the existence of a second disk is critical to understanding the formation scenarios of the young stars within the central parsec. For the self-gravitating accretion disk scenario, it is unlikely that two gas disks could exist simultaneously at the same radii since the disks would collide. Since the clockwise and counter-clockwise populations appear to have similar ages of $\sim$6 million years old to within $\sim$1 million years of each other [5], the existence of two stellar disks at the present epoch would mean that a second gas disk must have formed, become massive enough to collapse under self-gravity, and fragmented to form stars within, at most, 1 million years of the first gas disk. Likewise, for the infalling cluster scenario, two nearly perpendicular disks of stars most likely cannot be formed by the infall of a single star cluster. The existence of two stellar disks would arise from two clusters spiraling in within 6 million years of each other, as set by the clusters' ages, and would thus give an estimate of the frequency of such cluster infall events.

On the other hand, if there is only one disk plus a randomly scattered population, then it may be possible to explain all the stars within the central parsec with a single formation scenario with scattering events giving rise to out-of-the-plane members. This scenario has a difficulty in that IRS 13 appears to be a large cluster of young stars; which either does not lie on the common orbital plane or is counter-rotating within this plane. There is no obvious mechanism for drastically changing the orbit of the highest density portion of the young star disk.

Stars within the well-defined, clockwise disk appear to have high eccentricities ($\gtrsim 0.4$) which may be difficult to explain with a self-gravitating accretion disk formation scenario. Results from Nayakshin & Cuadra [22] indicate that stars born in a circular accretion disk would retain their nearly circular orbits well past the present epoch and currently there is little observational evidence for eccentric accretion disks within the sphere of influence of supermassive black holes in other galaxies (AGN). If the disk mass is built up from many small cloud-infall events, then the disk may circularize prior to becoming massive enough to form stars from self-gravity ($> 10^4$ $M_\odot$); however, for a single massive cloud infall or a cloud-cloud collision event, it remains to be determined if star formation can occur rapidly enough that the cloud's initial eccentricity is imparted to the subsequently formed stars before circularizing.

High eccentricity orbits may be more naturally explained in the infalling star cluster formation scenario. Stars that are stripped from a cluster as it spirals in should have a similar inclination, semi-major axis, and eccentricity as the cluster itself. Therefore, an infalling cluster with an initially eccentric orbit will produce a thin disk of stars with similarly eccentric orbits [23]. However, this formation scenario has its own share of unresolved issues including (1) the required high initial cluster mass ($> 10^5 - 10^6$ $M_\odot$, [24, 25]); (2) the required high central density, possibly even the presence of an intermediate mass black hole [26, 24]; and (3) the lack of observational evidence for tidally stripped stars at larger radii or X-ray emission from pre-main sequence low-mass stars within the central parsec [27].

In summary, the advent of laser guide star adaptive optics has allowed us to retroactively improve our 11 year astrometric data set used for monitoring stars orbiting our Galactic center. This has resulted in as much as a factor of ten improvement in proper motion precisions with resulting uncertainties of ∼1-2 km/s. As a result, we have attempted the first orbit fitting of the young stars proposed to lie in stellar disks orbiting the supermassive black hole. The individual orbits for the young stars confirm a disk of young stars at a high inclination rotating in a clockwise sense. The counter-clockwise rotating stars do not appear to be consistent with the previously proposed second disk. Stars within the well-defined, clockwise disk also appear to have high eccentricities, which is challenging to current accretion disk formation scenarios and provides a new observational constraint for models of star formation in the Galactic center.

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